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Ductile damage development in two-phase metallic materials applied at cryogenic temperatures

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ABSTRACT

FCC metals and alloys are frequently used in cryogenic applications, nearly down to the temperature of absolute zero, because of their excellent physical and mechanical properties including ductility. These materials, often characterized by the low stacking fault energy (LSFE), undergo at low temperatures three distinct phenomena: dynamic strain ageing (DSA), plastic strain induced transformation from the parent phase (γ) to the secondary phase (α') and evolution of micro-damage. Especially the third phenomenon leads to irreversible degradation of lattice and can accelerate the process of material failure therefore a suitable constitutive description appears to be fundamental for the correct analysis of structures applied at very low temperatures. The constitutive model presented in the paper takes into account the plastic strain induced phase transformation and the evolution of ductile damage. The FCC–BCC phase transformation results from metastability of LSFE metals and alloys at very low temperatures. The phase transformation process leads to creation of two-phase continuum where the parent phase coexists with the inclusions of secondary phase. Such heterogeneous material structure induces strong strain hardening related to two distinct mechanisms: interaction of dislocations with the inclusions and increase of tangent stiffness as a result of mixture of two phases, each characterized by different parameters. For the micro-damage evolution a generalization of the classical isotropic ductile damage concept (Chaboche, 1988a,b) to anisotropic model has been introduced. The kinetics of damage evolution is based on the accumulated plastic strain as driving force of ductile damage. The damage rate tensor depends on the strain energy density release rate (conjugate force) and on the tensor of material properties, that reflects the damage anisotropy.

1. Introduction

FCC metals and alloys (such as copper, copper alloys or stainless steel) are often applied in cryogenic conditions, down to the temperature in the proximity of absolute zero, because of their remarkable properties including ductility. A broad class of these materials is characterized by the low stacking fault energy (LSFE). Therefore, they undergo both dynamic strain ageing (DSA) and transformation from the parent phase (γ) to the secondary phase $\alpha')$ at extremely low temperatures. Both phenomena are accompanied by nucleation and evolution of micro-damage fields, driven by inelastic strains that develop at very low temperatures.

The present paper is focused on constitutive description of FCC materials applied at very low temperatures. As an example, Fe–Cr–Ni austenitic stainless steels are commonly used to manufacture components of superconducting magnets and

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cryogenic transfer lines since they preserve ductility practically down to 0 K. The constitutive description addresses two of three above listed phenomena driven by plastic strains at low temperatures: strain induced $\gamma \rightarrow \alpha'$ phase transformation and evolution of micro-damage. Both of them are of dissipative nature and lead to irreversible processes in the material lattice. Even if the metastable stainless steels have been chosen in the present paper as a field of application of the constitutive description, the model presented in the course of the paper can easily be adopted to describe other materials used at cryogenic temperatures (like copper, copper and aluminium alloys etc.). Their ductile behaviour down to 0 K implies evolution of plastic strain fields as soon as the stresses exceed the yield point characteristic of a given temperature.

During the plastic strain induced phase transformation that occurs in LSFE materials at low temperatures the γ austenite (FCC structure) is transformed into α' martensite (BCC structure). The presence of martensite platelets embedded in the austenitic matrix modifies the surrounding FCC lattice and implies local distortions (cf. Levitas and Ozsoy, 2009). The plastic strain induced phase transformation is at the origin of considerable evolution of material properties (strong hardening). According to Olson and Cohen (1975), the main mechanism contributing to the onset of $\gamma \rightarrow \alpha'$ phase transformation is the intersection of shear bands. The main parameters introduced by the authors are the temperature and the plastic strain. Choi et al. (2009) studied ductile failure of low-alloy multiphase transformation-induced plasticity (TRIP) steels as the result of plastic instability in the form of strain localization triggered by the microstructure-level inhomogeneity between the hard martensite phase and soft ferrite phase.

The plastic strain driven evolution of ductile micro-damage at cryogenic temperatures represents a dissipative and irreversible process that leads to creation of micro-cracks and micro-voids (micro-damage fields) and results in material "softening" (decrease of effective elasticity modulus). The relevant kinetic model of isotropic micro-damage evolution for ductile materials has been developed by Chaboche, 1988a,b, and Lemaitre (1992).

Stainless steels (typically: grades 304L, 316L, 316LN) applied at low temperatures prove unstable both with respect to plastic flow and to $\gamma \rightarrow \alpha'$ phase transformation. Three distinct domains of response of LSFE materials are indicated in Fig. 1 for one of the most frequently applied materials: stainless steel 316LN (cf. Obst and Nyilas, 1991). Domain I corresponds to the temperature range below T_1 and to the plastic flow instability called discontinuous or serrated yielding. Domain II stretches between T_1 and M_d, the latter being the temperature above which the process of plastic strain induced $\gamma \rightarrow \alpha'$ phase transformation does not take place. Inside this domain the plastic flow is smooth and accompanied by the transformation from parent γ phase to the secondary α' phase. The phase transformation leads to a significant increase of the yield stress. Finally, domain III above the temperature M_d is characterized by smooth plastic flow and rather stable behaviour with respect to the phase transformation. It is worth pointing out that the evolution of micro-damage occurs in all three domains and is driven by stable or unstable plastic flow. As all the above mentioned phenomena lead to irreversible degradation of lattice and can accelerate the process of material failure, a combined constitutive description is fundamental for correct prediction of critical state of the material.

The classical model of plastic strain induced $\gamma \rightarrow \alpha'$ phase transformation (Domain II) at low temperatures developed by Olson and Cohen (1975), attributes the onset of transformation to the intersection of shear bands. The authors have postulated for the so called TRIP steels a three parameter model capable of describing the experimentally verified sigmoidal curve that represents the volume fraction of martensite as a function of plastic strain. Other constitutive models available in the

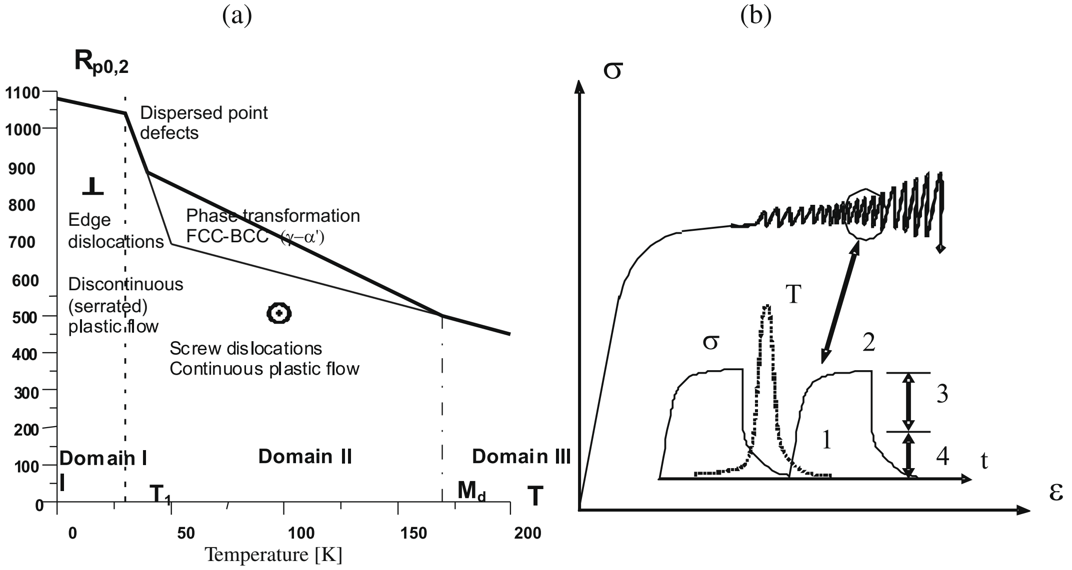

Fig. 1. (a) Three domains of response of LSFE materials applied at low temperatures (316LN) and (b) illustration of discontinuous plastic flow with four stages of the process.